Research Methods of Water Resources Carrying Capacity: Progress and Prospects

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Abstract: The study of water resources carrying capacity (WRCC), a major component of resources and environment carrying capacity (RECC), began relatively recently. However, WRCC has witnessed a rapid development in terms of concept, calculation methods, and empirical research in recent years. WRCC has become an important criterion for rational development and utilization of regional water resources. This paper first briefly reviews the development process of WRCC. It then evaluates and contrasts the representative research methods of conventional trend (CT), system dynamics (SD), multi-objective model analysis (MOMA), comprehensive evaluation (CE), and dynamic simulation recursive (DSR). The results show that although there are various methods of WRCC, the major methods used have become out-of-date and stagnant, and new more sophisticated methods and technologies are lacking. Specifically, our analysis found that the index system, scientific robustness and comprehensiveness of evaluation criteria of current research methods are insufficient and need to be improved. In addition, the dynamic research of WRCC should receive more attention, and it requires further study to make it more applicable to real-world uses. Finally, a set of monitoring and early warning systems should be established and applied in demonstration areas to meet the urgent needs of water resource management in the new era.

Key words: water resources; carrying capacity; research method; prospects

1 Introduction

Carrying capacity was originally a concept of mechanics; and taken to mean the maximum load that an object could bear without damage (Shi and Qu, 1992). After Malthus published his book An Essay on the Principle of Population in 1798, the concept of carrying capacity was gradually introduced into the resources and environment research field (Malthus, 1798). In 1838, a logistic equation based on Malthus's theory was proposed by Belgian mathematician Verhulst, and it is considered to be the earliest mathematical expression of resource and environmental carrying capacity (RECC) (Verhulst, 1838). In 1921, Park and Burgess used land resources as an example to propose the definitive concept of RECC (Park and Burgoss, 1921). As global problems such as resource exhaustion and environmental pollution have exploded since the 1960s and 1970s, the relationships between socio-economic activities and resources have been given increasing attention. RECC received considerable attention after the Roman Club published The Growth Limit in 1972 (Meadows et al., 1972), and related studies developed rapidly. At present, RECC is a significant issue related to the coordinated development of population, resources, and environment and it is also a key indicator for measuring regional sustainable development (Feng et al., 2017).

The study of water resources carrying capacity (WRCC), an important part of RECC, started relatively late. In many
overseas studies, WRCC is seen as an important factor for sustainable development, and is applied to such subjects as urban planning and agricultural production management, but few studies have focused on WRCC alone (Rijsberman and Ven, 2000; Brown, 2004). Due to the imbalance between water supply and water demand, China has paid more attention to WRCC research. In the early 1980s, Song and Sun discussed the population that water resources could support, which could be regarded as the early exploration of WRCC in China (Song and Sun, 1981). In the late 1980s, as increasing volumes of ecological water were diverted to social and economic consumption due to regional development in northwestern China, Shi and his Xinjiang Water Resources Research Group of the Chinese Academy of Sciences proposed that WRCC is the largest agricultural, industrial, urban, and population level that can be maintained by the water resources in a region without destroying social and ecological systems at a certain stage of social, scientific, and technological development. Thus, WRCC is a dynamic and integrated goal, which may vary with the development of the social economy, science, and technology (Shi and Qu, 1992).

After the concept of WRCC was proposed, it immediately aroused the attention of academics. Many scientific research projects were launched in this field to promote the development of WRCC in China. As the research continued, the understanding of the concept and connotation of WRCC was gradually expanded. WRCC not only referred to the population that water resources could support under a certain living standard and socio-economic scale (Song and Sun, 1981; Xia and Zhu, 2002; Feng and Liu, 2006) but it also considered the amount of human utilization the water resources could supply sustainably (Xu, 1993; Feng and Liu, 1997). For the connotation of WRCC, the diversity and comprehensiveness of carrying objects were given more attention, and WRCC gradually evolved to represent the ability to support a social-economic-ecological system of water resources (Xia and Zhu, 2002; Feng et al., 2014).

With the necessity of improving WRCC, several domestic scholars have undertaken deep studies to solve certain problems, such as non-uniform indices, incomparable results, and the loss of practical applicability after 2000. By combining land resources carrying capacity (LRCC) with WRCC, Wang et al. (2004) used the balance analysis method of agricultural product price exchange ratio to calculate the future WRCC of Northwest China. Cheng (2002) and Yao et al. (2005) discussed the essence of WRCC, pointing out that WRCC would have a changing value under the influence of human value choices, cultural background, institutional forces, and other factors, and that it would change with the variations of regional development goals.

2 Primary research methods of WRCC

The research methods of WRCC are becoming increasingly diversified; however, most of these methods can be divided into two types according to their aims. The aim of the first type is to calculate the population or economic scale that water resources can support based on water supply and demand, and it includes the conventional trend method (CTM) and dynamic simulation recursive (DSR). The aim of the second type is to evaluate regional WRCC and confirm the potential development of water resources, and this type includes comprehensive evaluation (CE) and multi-objective model analysis (MOMA). System dynamics (SD) has characteristics of both types of methods.

2.1 Conventional trend method (CTM)

Conventional trend method (CTM) is a typical WRCC research method and is based on statistical analysis. CTM focuses on regional ecological water demand and the rational allocation of water resources demand in the relevant socio-economic departments. The procedures of CTM are to first select one or more reference indices to analyze the future water supply and demand, and then to calculate the population, economic scale, or city scale that regional water resources can support while maintaining the balance between water supply and water demand.

The study of CTM started relatively early. After Shi and Qu (1992) proposed the concept of WRCC, they used CTM to analyze and forecast the water supply and demand and WRCC of Urumqi River Basin of Xinjiang in 2000. Since that study, CTM was applied in WRCC research of arid and karst areas by several scholars (Qu and Fan, 2000; Wang and Liang, 2001), which expanded the scope of application and the progress of CTM.

The advantages of CTM are simple, intuitive and operable. The results of CTM can reflect the regional WRCC (Cheng, 2002; Zhang et al., 2007; Duan et al., 2010). However, CTM focuses more on individual factors of WRCC. CTM ignores the interactions between the various factors of the socio-economic system; thus, it does not fully reflect the regional WRCC. Nevertheless, many academics still agree that CTM provides several useful references for the coordination of research of complex systems (Cheng, 2002).

2.2 System dynamics (SD)

Jay Forrester of the Massachusetts Institute of Technology was the first to propose system dynamics (SD) in the 1970s (Forrester, 1971). SD focuses on analyzing the dynamic changes in complex systems, including four basic elements: stock, flow, feedback, and time delay.

The stock can be regarded as a component or subsystem of the system. The stock represents the quantity of material, information, or funds of the system in a specific period. The flow is divided into inflow and outflow, and may be described as input and output according to the stock. After the
material, information, or cash flow into the stock, the stock stores and processes them and later outputs, or feeds back the input flow through a ‘valve’. A time delay may occur in almost every step of the process, which is why SD can be seen as a ‘dynamic’ research method (Qi, 1987).

SD was introduced into the field of RECC gradually and was successfully applied in The Growth Limit by Roman Club (Meadows et al., 1972). The procedures of SD follow four steps. First, the whole system is divided into several parts or subsystems; second, the causality of every part or subsystem is analyzed; third, the causality, status, and control of the status of every component of the system are shown by the system flowchart; and finally, the system equations need to be established for running a simulation to determine the optimal project for regional WRCC (Duan et al., 2010).

Compared with CTM, SD can grasp the relationships among the various components of the system, and it is suitable for dealing with complex, nonlinear problems and dynamic trend research over long time frames due to its systematic nature (Cheng, 2002; Duan et al., 2010). SD is widely used in WRCC research. Many scholars establish SD models to analyze WRCC in arid, semi-arid, and metropolitan areas to provide guidance and policy recommendations for water resources management, regional sustainable development, and urban planning (Fang and Yu, 1999; Wang et al., 1999; Li et al., 2000; Fan et al., 2005; Niu et al., 2009).

However, SD is complicated because of its dynamic nature and numerous subsystems, and it is difficult to obtain an accurate result of WRCC. Proper selection of parameters is also a problem, since it is easily affected by the modeler’s cognitive understanding of the system, which could lead to unreasonable conclusions (Cheng, 2002).

### 2.3 Multi-Objective model analysis (MOMA)

The idea of using multi-objective model analysis (MOMA) to study WRCC is derived from sustainable development theory. The relationships between water resources, socio-economic system development, ecological environments, or other natural resources should be considered since the research object of WRCC is a macro-system of both nature and society. Therefore, WRCC research should take into consideration the multi-objective dimensions of the nature and society macro-system, rather than a signal object, to obtain an optimal solution through weighing different objects in order to coordinate the development between water resources, socio-economic factors, and the resources environment (Xu and Cheng, 2000a; Cheng, 2002; Fu et al., 2010).

MOMA provides a new dimension for WRCC research. The main advantages of MOMA are that it is comprehensive, so it can analyze the dynamic relations between water resources and other factors of the regional social and economic system and resources and the environmental system. Additionally, compared to other methods, which focus on the evaluation of WRCC, MOMA concentrates more on the water resources development plan because it can establish a multi-objective model to obtain a satisfactory result of a water resources development project (Duan et al., 2010).

In 1995, Weng et al. first introduced MOMA into WRCC research. These researchers advanced a comprehensive set of water resources planning schemes for North China. Since that study, the Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, adopted MOMA to establish a WRCC analysis model and calculate WRCC in Heihe River Basin in order to provide suggestions about water resources utilization and regional sustainable development of the Heihe River Basin (Xu, 1999; Xu and Cheng, 2000a, 2000b). In recent years, many scholars have attempted to apply it to WRCC analysis of large-scale, semi-arid, semi-humid, and urban areas, which are believed to expand the application scope of MOMA (Zhu et al., 2004; Wu and Chen, 2009; Fu et al., 2010; Zhang et al., 2013).

Unfortunately, it is difficult to identify a perfect method for calculating MOMA, though it is suitable for complex macro-systems of nature and society. A common solution is to convert the multi-objective system into several single targets, but studies often lack objectivity in selecting the planning objectives and the weights of the indices because they are determined by the researchers themselves (Zhang et al., 2007).

### 2.4 Comprehensive evaluation (CE)

Comprehensive evaluation (CE) is a methodology based on water supply and water demand that is used to assess regional water resources carrying status. The procedures of CE are as follows: first, select indices which may affect WRCC; second, set the weight of each index; third, establish the evaluation index system of WRCC; and finally, evaluate the regional water resource carrying status (Duan et al., 2010).

CE is praised for its comprehensiveness and extensive applicability. CE is suited for the evaluation of WRCC at different scales through combining it with regional sustainable development theory (Dong and Liu, 2010; Liu et al., 2011; Qu, 2017). Many scholars also combine CE with other methods, such as fuzzy comprehensive evaluation, matter-element extension model, and BP neural network and gray correlation model in regional WRCC research in order to strengthen the comprehensive and scientific robustness of the results (Min et al., 2004; Zhang et al., 2011; Kang and Song, 2010; Yang et al., 2016).

It is critical to establish a scientific and comprehensive WRCC evaluation index system for CE, which is directly related to the accuracy of the evaluation results. However, similar to the MOMA, the indices and weights in CE are...
also determined by researchers, which may undermine the accuracy of evaluation results (Duan et al., 2010).

2.5 Dynamic simulation recursive (DSR)

Dynamic simulation recursive (DSR) is a methodology used to calculate regional water supply and water demand in the future by combining dynamic simulation with mathematical economic analysis, and DSR is based on the balance of water supply and water demand. The variables and construction of the model can be revised to make the model consistent with the real situation after comparing calculated values with actual values (Feng, 2000).

Compared to other methods, DSR focuses more on the exploration of the maximum regional WRCC to establish a ‘red line’ for regional water resources development and utilization. DSR is closer to the physical meaning of carrying capacity than other methods, which is more fruitful for WRCC research. In practical research, DSR is frequently applied in regional water resources development and management. After analyzing the water supply and the regional development scale, the threshold of regional water carrying capacity is developed (Li et al., 2000; Gu et al., 2005; Xu et al., 2011).

However, the quality of data used in DSR must be high, and a long time series is necessary for analysis. If the data quality cannot meet the needs of DSR, it is likely to negatively affect the simulation process, and the results.

In addition to the methods mentioned above, the background analysis method, simple quota algorithm, projection pursuit analysis method, gray association analysis, artificial neural network method and water footprint method are also common analysis methods in WRCC research (Chen, 1995; Wang et al., 2000; Liu and Chen, 2007; Ma et al., 2012). It is worth noting that the integration of various methods has become an important trend in WRCC research, and the diversity and comprehensiveness of research methods are gradually being strengthened.

3 Conclusions

Although the concept of WRCC was proposed relatively recently, WRCC research has developed rapidly in terms of basic concepts, connotation, calculation methods, and empirical research applications. WRCC has become an important factor in regional water resources development, industrial development, and the establishment of water resources policy.

However, it has been noted that there are several problems with WRCC research that need to be solved. Although the current research methods of WRCC are numerous, and the research results are abundant, the basic calculation methods have not changed since they were proposed more than ten years ago. Most researchers focus on applying these existing methods to different regions instead of creating new methods that may be more optimal for local conditions.

Thus, Zuo (2017) believes that WRCC research has entered a ‘bottleneck’, and new ideas and technical methods need to be promoted. Additionally, since the research object is a macro-system of nature and social economy, the relationships among internal components of the system are intricate. This aspect causes problems when using existing research methods to analyze the macro-system, such as the arbitrariness of the evaluation criteria and the imperfect index system, which can affect the accuracy of the research results, especially for MOMA and CE.

In addition to exploring new research methods and technologies, discussing the relationships among water resources, natural systems, and socio-economic systems is an essential trend of WRCC research to make the results more practical. It is worth noting that water supply and water demand are changing under global changes and rapid urbanization due to the dynamics, randomness, and uncertainty of water resources, which leads to variations of WRCC. Therefore, it is necessary to promote dynamic simulation in WRCC research to reveal the variation of WRCC. Additionally, a set of standard evaluation, monitoring, and early warning systems of WRCC should be established and applied in a national ecological civilization demonstration area or a water-deficient area to meet the requirements of water resources management in this new era (Feng et al., 2017).

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摘 要：作为资源环境承载力主要组成部分，水资源承载力研究起步较晚，但近年来无论在概念、计算方法还是实证研究等方面均有较快发展，也已成为区域水资源合理开发与利用的重要判据。本文简要回顾了一下水资源承载力的发展历程，选取常规趋势法、系统动力学方法、多目标模型分析法、综合评价法和动态模拟递推法为代表对水资源承载力的主要研究方法进行评述与对比，研究认为：（1）水资源承载力的研究方法虽然种类较多，但主要方法往往已定型多年，新方法与新技术较为欠缺；（2）当前主要研究方法在指标体系、评价标准制定的科学性、全面性等方面尚显不足，需要进一步完善；（3）未来水资源承载力需要加强动态研究，同时注意与实际结合，尝试建立一套监测预警体系并选取部分地区进行先行示范，满足新时期水资源管理的需求。

关键词：水资源；承载力；研究方法；展望